Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE)

Lunar Advanced Volatile Analysis (LAVA) Integration and Testing – Evaluation of Lee Valve

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Abstract

The Resource Prospector (RP) mission with the Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE) payload will prospect for water within the lunar regolith and provide a proof of concept for In-Situ Resource Utilization (ISRU) techniques, which could be used on future lunar and Martian missions. One system within the RESOLVE payload is the Lunar Advanced Volatiles Analysis (LAVA) subsystem, which consists of a Fluid Sub System (FSS) that transports volatiles to the Gas Chromatograph-Mass Spectrometer (GC-MS) instrument. In order for the FSS to transport precise and accurate amounts of volatiles to the GC-MS instrumentation, high performance valves are used within the system. The focus of this investigation is to evaluate the redesigned Lee valve. Further work is needed to continue to evaluate the Lee valve. Initial data shows that the valve could meet our requirements however further work is required to raise the TRL to an acceptable level to be included in the flight design of the system. At this time the risk is too high to change our baseline design to include these non-latching Lee solenoid valves.

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Nomenclature

C	=	Celsius (degrees)
ETU	=	Engineering Test Unit
GC	=	Gas Chromatograph
ISRU	=	In-Situ Resource Utilization
LAVA	=	Lunar Advanced Volatile Analysis
MS	=	Mass Spectrometer
NIRVSS	=	Near Infrared Volatile Subsystem
NSS	=	Neutron Spectrometer Subsystem
OVEN	=	Oxygen Volatile Extraction Node
psia	=	Pounds per square inch absolute
PT	=	Pressure Transducer
RESOLVE	=	Regolith and Environment Science and Oxygen Lunar Volatile Extraction
WDD	=	Water Droplet Demonstration

I. Introduction

The US National Aeronautics and Space Administration (NASA) is preparing for the Resource Prospector (RP) mission currently planned for launch in 2020 to one of the lunar poles. The Resource Prospector mission, with Regolith & Environment Science and Oxygen & Lunar Volatile Extraction (RESOLVE) as its primary payload, is designed to extract and process resources on the lunar surface into useful products through In-Situ Resource Utilization (ISRU). ISRU will allow for propellants, breathing air, and construction materials to be manufactured on the moon, mars, and other planetary bodies throughout the duration of the mission. These materials can support the spacecraft and astronauts' daily functions and eventually support travel to other locations within the solar system. This will greatly reduce the mass launch load, and ultimately reduce the cost of missions and expand the lifetime and capability of exploration missions.

The Lunar Advanced Volatile Analysis (LAVA) subsystem, a part of the RESOLVE payload, is designed to transport volatiles driven off of lunar regolith samples using the Fluid Subsystem (FSS) and process and analyze those volatiles in search of water vapor using a gas chromatograph – mass spectrometer (GC-MS) coupled analytical instrument. In follow-up ISRU missions, water vapor will be electrolyzed into oxygen and hydrogen to be used as mission combustibles. If water

is identified and captured within the LAVA subsystem, it will be cooled, condensed, and photographed in the Water Droplet Demonstration (WDD) assembly. The RESOLVE instrument suite also includes the Neutron Spectrometer Subsystem (NSS), Near Infrared Volatile Subsystem (NIRVSS), Drill, and Oxygen and Volatile Extraction Node (OVEN) subsystem. The focus of this research was within the LAVA subsystem, specifically the FSS, which is displayed with OVEN below in Figure 1.

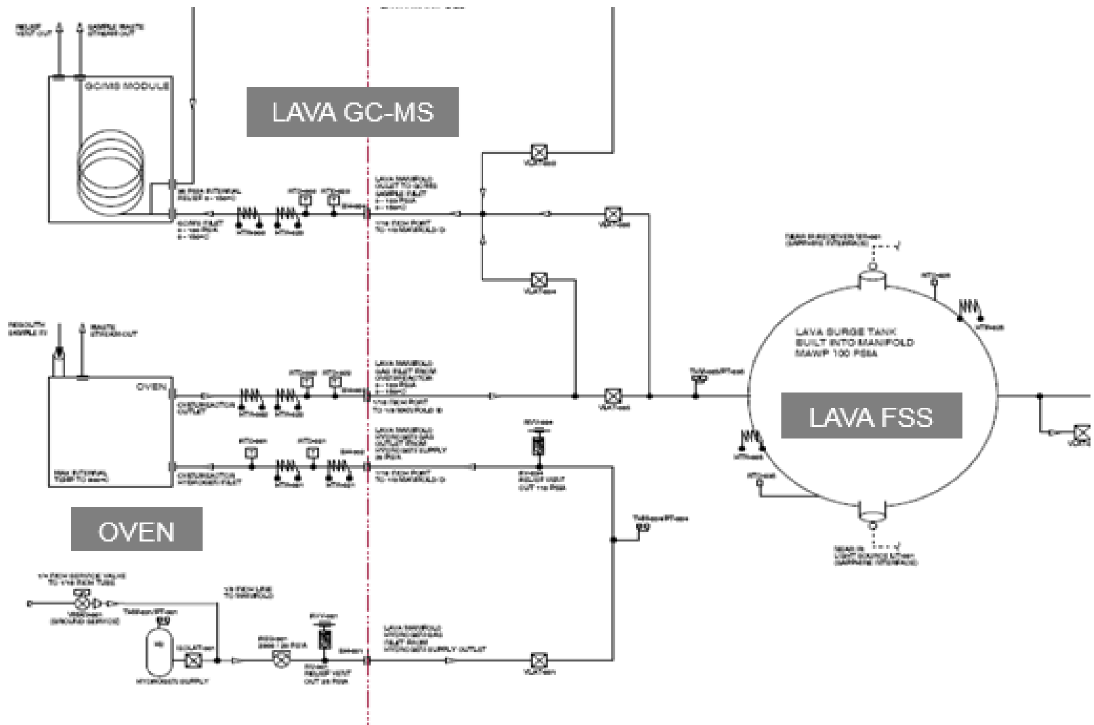

Figure 1. OVEN and LAVA interface

The LAVA FSS contains valves and pressure transducers (PT) that control and monitor the flow of gas throughout the system. Within the Engineering Test Unit (ETU) FSS, there are 12 valves and 7 PTs. The functionality of these components is essential to accurate and precise data. The valves and PTs chosen for flight are required to withstand high temperatures (152C) and high pressures (100psia).

The objective of this research is to integrate and test Lee valves under "flight like" conditions in order to determine if they are a suitable replacement for the baseline, Mindrum, valves in the FSS. A Mindrum valve within the FSS is depicted in Figure 2, while the desired replacement, Lee valve, is depicted in Figure 3. In order to perform these tests, a laboratory setup was designed and constructed and a LabView program was created for monitoring and data collection. A second objective of this research is to test and integrate different pressure transducers under "flight like" conditions to determine an appropriate PT configuration to move flight forward. For the PT testing, two test manifolds were designed and manufactured and a LabView program was created for monitoring and data collection.

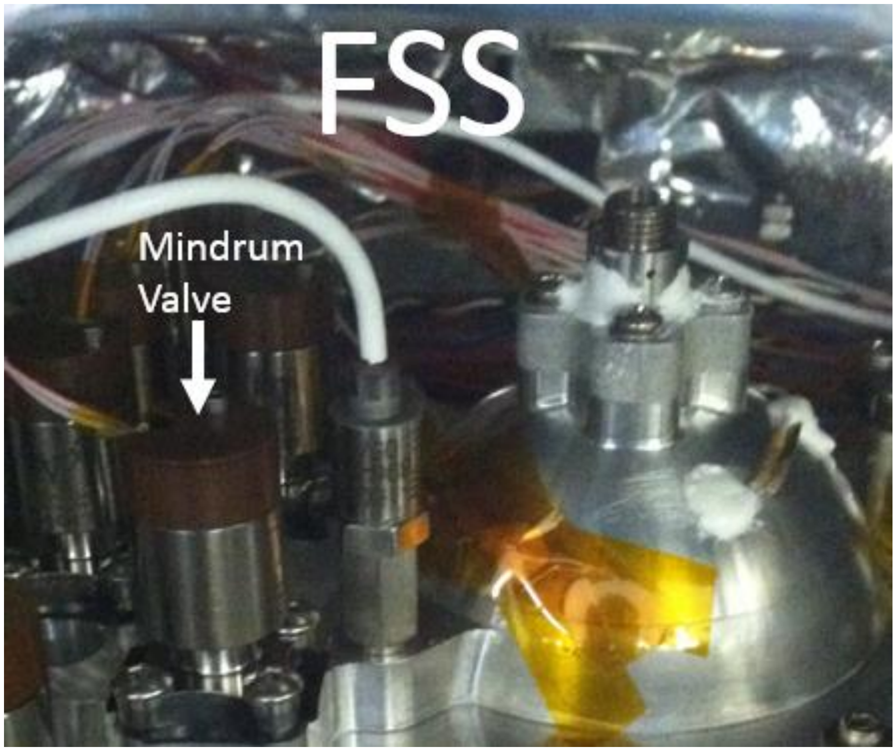

Figure 2. Mindrum valve within the FSS

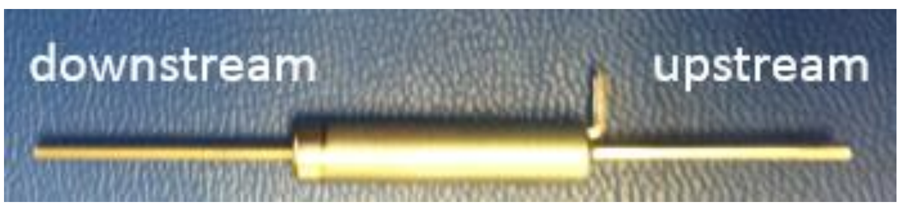

Figure 3. Lee valve

II. Experimental Methods

Experimental setups were designed and built for both the valve and PT integration tests. The valves and PTs were tested to similar stress conditions normally tested within the LAVA FSS. Simulating flight-like stress conditions while testing the PTs and valves allows for evaluation of the component functionality and provides confidence in the reliable performance of the selected components during the mission.

A. Lee Valve Test Experimental Methods

An experimental setup was built to represent the airflow and temperature stresses present on the Lee valves in the FSS. Table 1 displays the power and energy load measurements for the Lee valve operation. Figure 4 displays the Lee valve test experimental schematic. As shown in the schematic, a gas supply containing either air, helium or nitrogen is applied to one side of the Lee valve, while a vacuum is pulled on the other side of the Lee valve. A PT is placed on the pressurized side of the valve to determine if there are any leaks through the Lee Valve. Half of the tests conducted were with pressurization of the Lee valve on side A and the other half were with pressurization of the Lee valve on side B (with a setup that mirrors the schematic below). Figure 5 displays the actual

laboratory setup for a side B experiment. All of the Lee valve tests conducted with data collection were controlled by a novel LabView program, displayed in Figure 6 and Figure 7. The LabView program allows the user to track temperature and pressure and to actuate the Lee valve.

Table 1. Lee valve power and energy load

Valve Operation	Power	Time	Energy
Latch	~9W	10ms	24.3 µWh
Hold	~0.25W	2 minutes	8.325mWh
Hold	~0.25W	5 minutes	20.8mWh

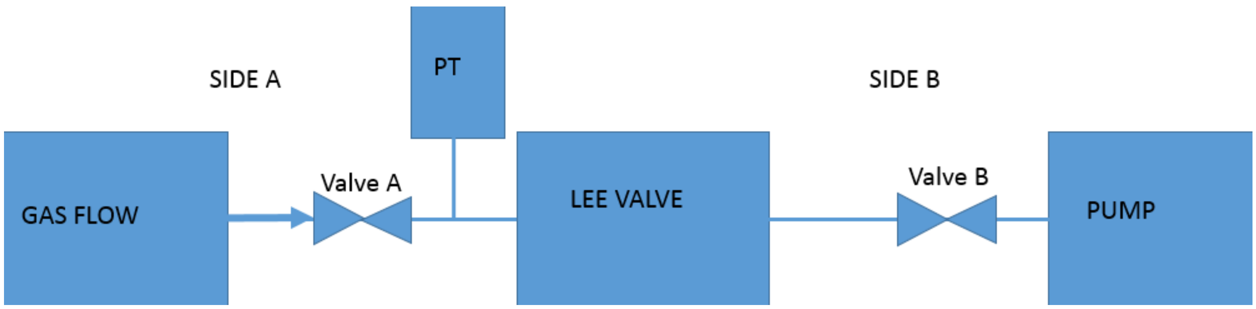

Figure 4. Side A Lee valve experimental schematic

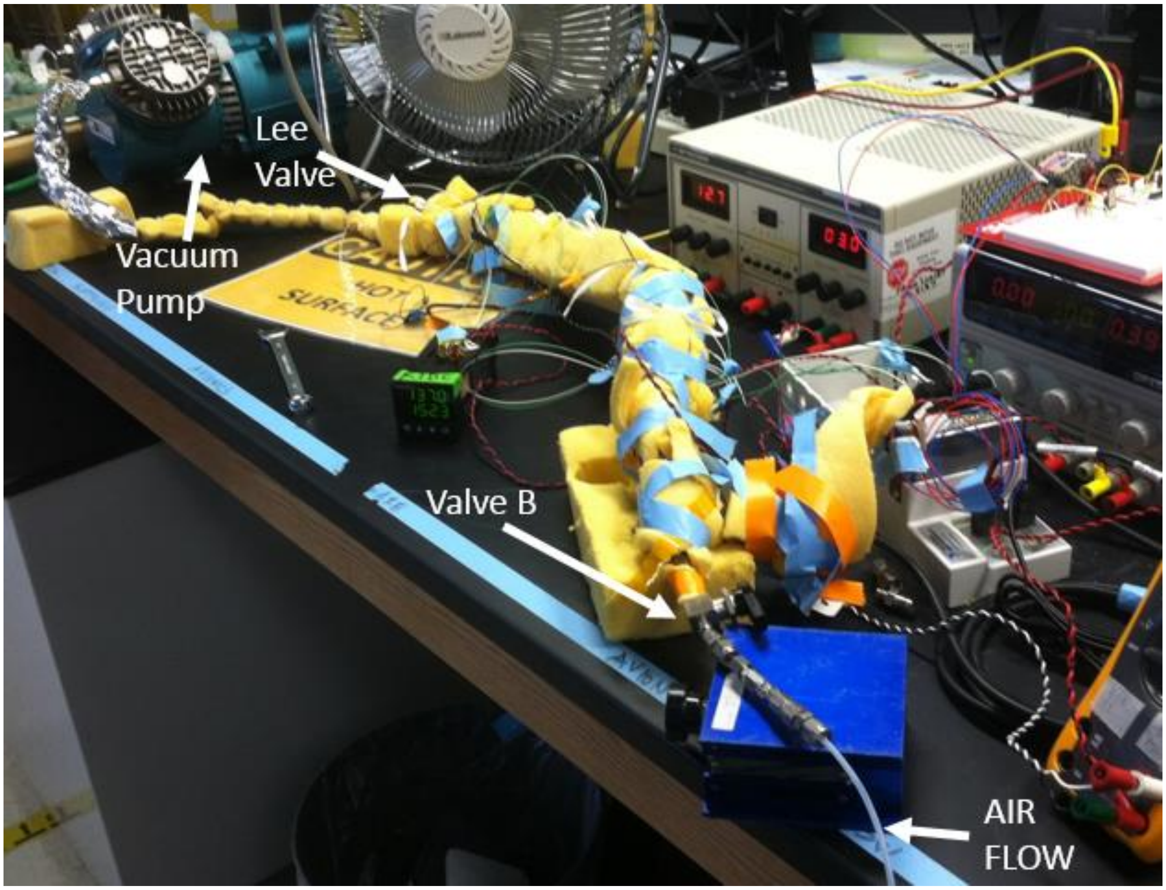

Figure 5. Side B Lee Valve experimental setup

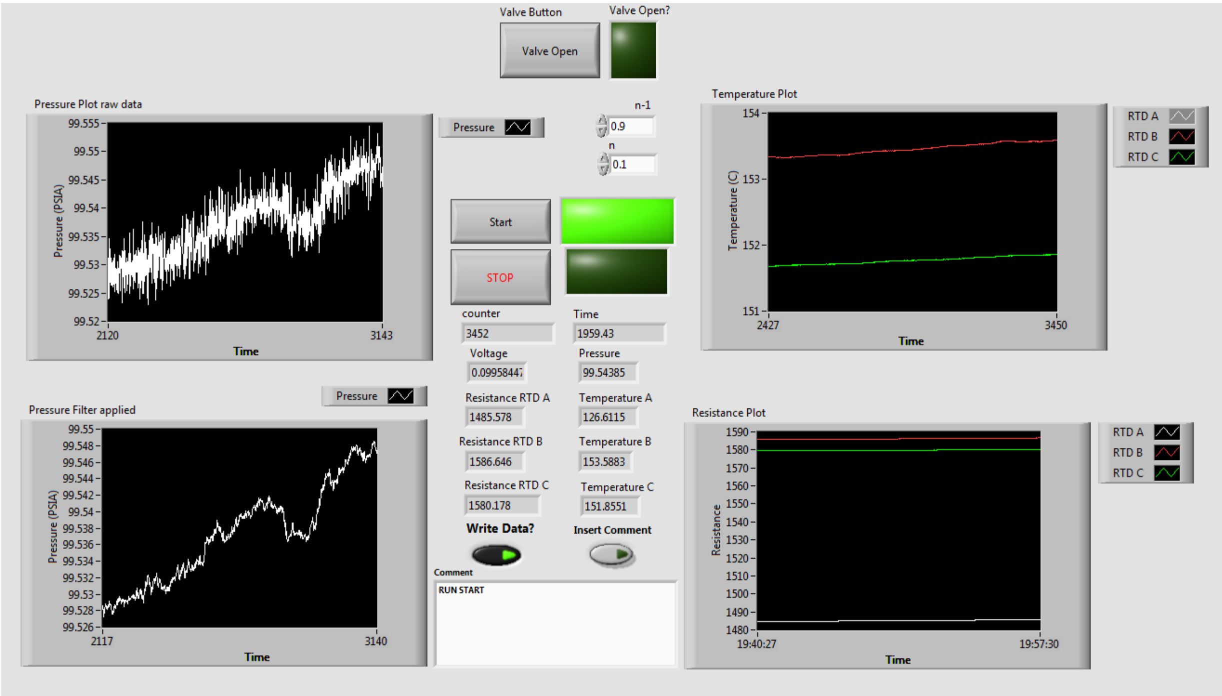

Figure 6. Lee valve testing LabView Front Panel

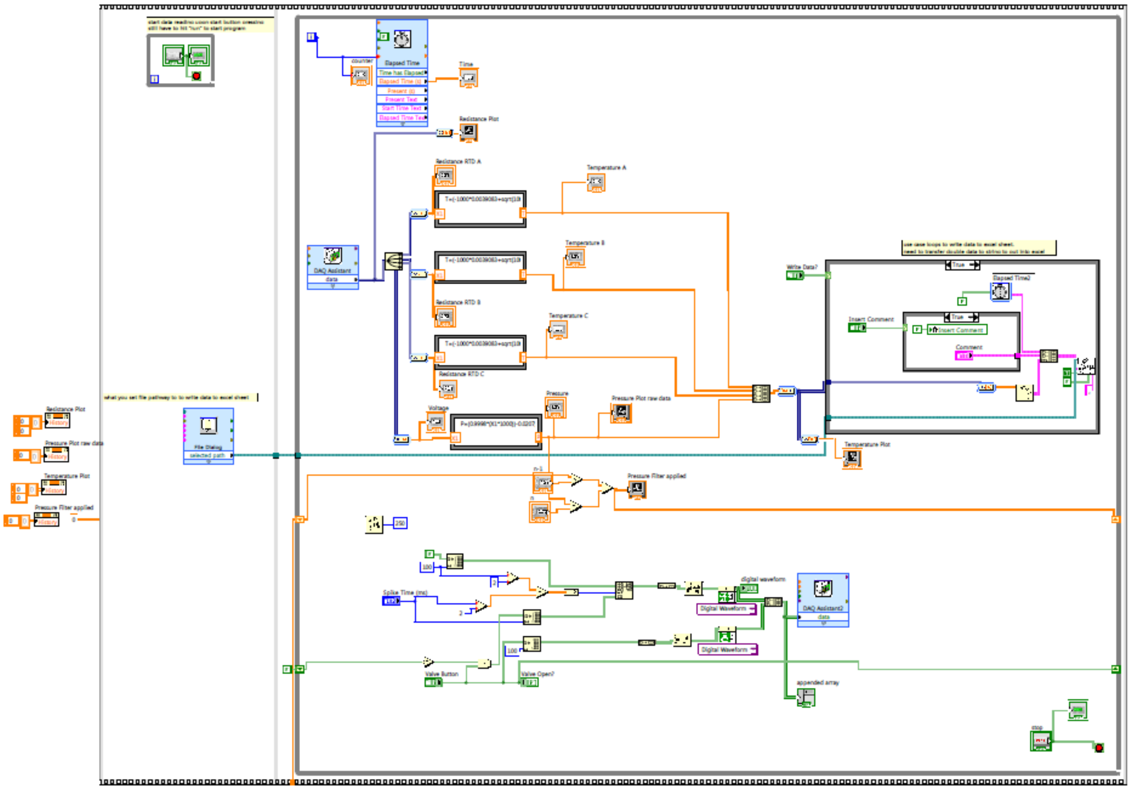

Figure 7. Lee valve testing LabView code

First, a series of pressure tests were conducted to stress the Lee valve with high pressures for a long duration of time at high temperature. For the pressure tests, the temperature was held constant between 155C-170C (depending on the ability of the heater to reach those temperatures). The pressure supplied to one side of the Lee Valve was held at 45psia, 65psia, 85psia and 100psia for 1 hour each. Three trials were conducted on side A and three trials on side B of the Lee valve. For each trial and pressure increase, the gas flow was increased and valve A/B was opened to allow increased pressure to reach the Lee valve. After the pressure was increased, valve A/B was closed and the backing pressure from the gas flow was released. When side A was pressurized, valve B was constantly open and the pump was on to pull a vacuum on side B and vice versa when side B was pressurized.

After the pressure tests were completed, the Lee valve was stressed with high pressures and high temperatures through temperature cycling tests. For the temperature cycling tests, the temperature of the Lee valve was kept at a constant temperature between 150C-155C (depending on the ability of the heater to reach those temperatures). For each trial, the valve was actuated 5 times when the constant temperature was reached and one side of the valve was pressurized to 100psia for 1 hour. After the pressure was increased, valve A/B was closed and the backing pressure from the gas flow was released. When side A was pressurized, valve B was constantly open and the pump was on to pull a vacuum on side B and vice versa when side B was pressurized. After the pressure was held for 1 hour, the Lee valve was actuated another 5 times to release the

pressure. At the end of each run, the temperature of the Lee valve was cooled down to 25C-40C. Side A and side B both experienced 25 temperature cycles each.

Finally, electrical switch delay tests were performed on the Lee valve. The electrical switch delay tests consisted of pressurizing each side of the Lee valve 25 times each, and releasing the pressure by commanding the Lee valve to actuate in the created Labview program. The time delay between actuating trigger and response was then measured.

III. Results and Analysis

The resulting data from the Lee valve tests is depicted graphically and in tables to help better display the Lee valve performance over time with multiple pressure and temperature cycles.

A. Lee Valve Tests Results

Data was first collected and analyzed for the long duration, high temperature, and pressure tests. For the pressure tests, the temperature was kept constant between 155C-170C. The pressure placed on the Lee valve was held at pressures of 45psia, 65psia, 85psia and 100psia for 1 hour each. Figure 8 graphically displays the net pressure change, at held pressure of 45psia, and the net temperature change over time. Every pressure hold tested for each of the six trials was plotted and the pressure change from the beginning to the end of the hour pressure hold was recorded. The change in pressures for each pressure hold and trial were compiled and are displayed in Table 2.

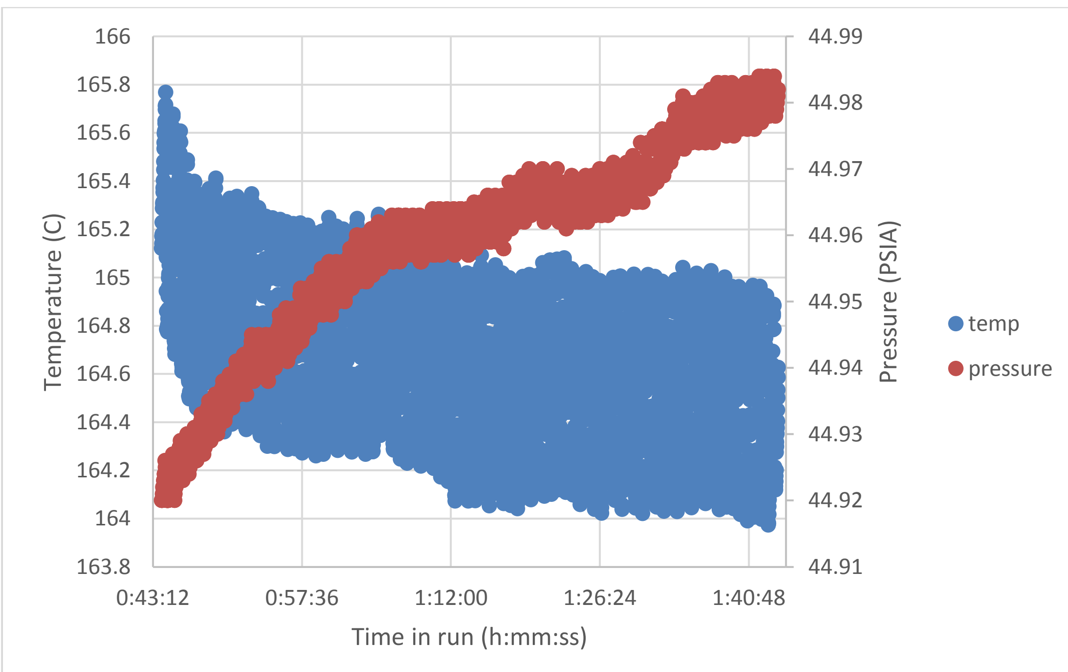

Figure 8. Graphic depiction of the change in temperature and pressure over time for 45psia pressure hold in a Lee valve pressure test

Table 2. Leak rate data for all Lee valve pressure tests

Pressure set (psia)	Upstream			Downstream		
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
45	0.08	0.1	0.065	0.007	0.06	0.018
65	0.04	0.03	0.13	0.05	0.07	-0.02
85	0.04	0.055	-0.033	-0.09	0.05	-0.02
100	-0.05	-0.07	-0.025	-0.16	0.03	0.01

Take note that the results displayed in Table 2 are the average leak rates in psia per hour. Also take note that leak rates below 0.1psia/hr are considered acceptable by the LAVA team based on prior analysis of the FSS. Therefore, a negative delta change in pressure below 0.1psia/hr is considered stable and functioning, as shown by the value highlighted in green. If the leak rate is greater than 0.1psia/hr, in the negative or positive direction, it is considered unstable and a sufficient leak, indicated by the value highlighted in red. Overall, the pressure tests conducted display a functioning, acceptably leak tight Lee valve, with one outlier in Trial 4 at 100psia.

One possible cause of a net increase in pressure could be thermal disequilibrium in the system, thus causing the helium to heat up and gain energy as the run proceeds. This could result in a slight increase in pressure as the system strives to reach thermal equilibrium. A slight decrease in net pressure could also be due to the system striving to reach equilibrium. Slight changes in net pressure could also be due to instrumental or human error.

Lee valve temperature cycle tests are currently underway. Data has been collected and analyzed for high temperature, high pressure, 1-hour long temperature cycle tests. The pressure change during a 100psia pressure hold for 1 hour after cooling down then heating up the experimental setup and actuating the valve 5 times before the run was calculated. The calculated leak rates in psia/hour for each run tested with pressurization both downstream and upstream of the valve were compiled and are displayed in Table 3.

Table 3. Leak rates for the Lee valve temperature cycle tests

Comments	Trial	Downstream	Upstream	Trial	Comments
	1	0.25	0.21	26	fan
	2	0.1	0.6	27	large temp increase
	3	0.225	0.44	28	Unstable temp?
	4	0.045	0.66	29	fan
	5	0.045	0.3	30	fan
	6	0.14	0.46	31	fan
	7	0.04	0.25	32	fan
	8	0.08	0.2	33	fan
	9	0.05	0.79	34	fan
	10	-0.02	0.63	35	fan
	11	0.14	-0.09	36	*air cooled, let stabilize at 160C 30min
	12	0.06	-0.06	37	*air cooled, let stabilize at 160C 30min
	13	0.05	0.3	38	*air cooled, let stabilize at 160C 30min

	14	0.16	0.065	39	*air cooled, let stabilize at 160C 30min
	15	0.04	0.17	40	*air cooled, let stabilize at 160C 30min
after lunch	16	0.1	0.25	41	moved pump, less vibration in line, air cooled, 160C for 30 min
	17	0.015	0.15	42	160C for 1hr
	18	0.17	0.08	43	air cooled, 160C 30min
fan	19	0.11	0.07	44	air cooled, 160C 30min
fan	20	0.045	0.08	45	air cooled, 160C for 10min
fan	21	0.035	0.18	46	160C 1hr
fan	22	0.045	-0.05	47	at higher temp for 3hrs, decreased temp from 168C-164C
fan	23	0.18	0.17	48	160C 1hr
fan	24	0.045	-0.04	49	160C 3 hrs
fan	25	0.072	0.06	50	160C 30min

Take note that the results displayed in Table 3 are the average leak rates in psia per hour. Also take note that leak rates below 0.1psia/hr are considered acceptable by the LAVA team based on prior analysis of the FSS. Therefore, a negative delta change in pressure below 0.1psia/hr is considered stable and functioning, as shown by the value highlighted in green. If the leak rate is greater than 0.1psia/hr, in the negative or positive direction, it is considered unstable and a sufficient leak, indicated by the value highlighted in red. The first trial performed on a given day is highlighted yellow.

Take note that the largest net change in pressures usually occurs during the first trial of the day. Even though the RTDs on the system read a constant temperature, the large net pressure change in the first trial of the day could be due to the system attempting to reach thermal equilibrium after several hours overnight at room temperature. Furthermore, Trial 16 downstream was performed after lunch, which may have allowed the system to completely cool down, taking it out of thermal equilibrium. Additionally, from Trial 17 downstream onward, a fan was used to cool down the system more quickly after each trial.

Take note that Trials 47 and 49 had a “heat up wait time” of 3 hours. Also take note that those trials displayed some of the lowest pressure changes in all of the trials tested. These two trials suggest that the system needs extended time to reach thermal equilibrium before testing begins, especially at the beginning of the day. Further tests should be conducted where the “heat up wait time” is longer than 1 hour to help confirm if thermal differences lead to the larger pressure differences in the preliminary tests.

Also, take note that the upstream tests displayed more “red” or unacceptable pressure changes. This could not only be due to a thermo disequilibrium for the first run of the day, but also due to the fact that on the upstream side has a 2.25 ratio of not heated line to locally heated line, while the downstream side has a 0.56 ratio of not heated to heated line. The drastic difference in local heating could also lead to thermal differences in the line, leading to larger temperature differences, particularly increases.

Furthermore, the downstream side of the valve had more than twice the length of pressurized line than the upstream side. During the experimental design process, this was not thought to make an impact. The downstream was initially lengthened to accommodate the heater used. A smaller pressurized volume on the upstream side could lead to larger changes in pressure with smaller molecule thermal differences. This is due the ideal gas law, where if there are less molecules present, thermal differences and energies between them will present a greater difference in the average molecule energy (pressure) throughout the run. This could also potentially explain the differences in the results from the upstream side and the downstream side.

In addition to the thermal cycling and pressure tests on the Lee valve, actuation temperature change tests were performed. Actuation temperature tests were performed to determine the temperature change on the Lee valve when it is actuated for a given period of time. Tests were performed primarily at a baseline temperature between 162C-164C. A five minute actuation test was also performed at a baseline temperature of 152C, which is normal operating temperature for the valve in the FSS system, and compared to that at 162C-164C. Table 4 and Figure 9 display the average temperature changes for five trials for 5 short actuations, 30 second, 1 minute, 2 minute and 5 minute actuations when the line is both pressurized and at atmospheric pressure (no pressure). Table 5 and Figure 10 display the average temperature increase and standard deviation of 5 minute actuations at both a 162C and 152C baseline temperature.

Table 4. Average temperature increase and standard deviation for Lee valve actuations

Actuations	average temp inc (deg C) pressure	std deviation pressure	average temp inc (deg C) no pressure	std deviation no pressure
5 short	0.1436958	0.020993337	0.2543146	0.056326434
30 sec	1.7784676	0.257379217	1.6081342	0.061175371
1 min	2.6567006	0.094780924	2.8945894	0.056692041
2 min	3.9407512	0.455062204	4.672594	0.213456402
5 min	7.1876274	0.934053555	8.1067726	0.926178799

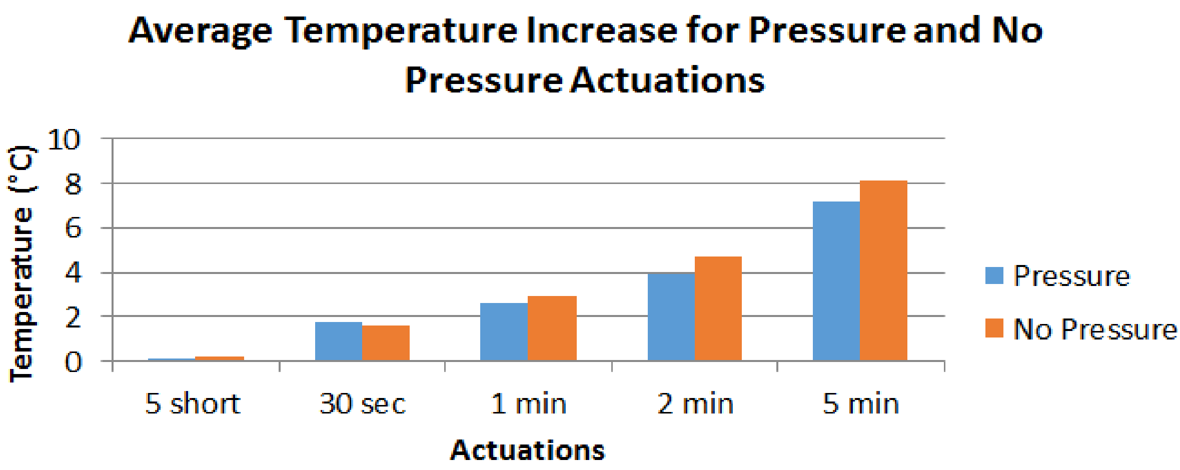

Figure 9. Graphical representation of valve temperature increase for various time open durations with and without pressure in the fluid line. Valve is at 163C

Table 5. Average temperature increase for 5 min actuations at 163C and 152C baseline temperatures

Actuations	Average temp inc (deg C) pressure	std deviation pressure	Average temp inc (deg C) no pressure	std deviation no pressure
5 min at 162C	7.1876274	0.934053555	8.1067726	0.926178799
5min at 152C	7.0791862	0.211371896	7.3573744	0.648472465

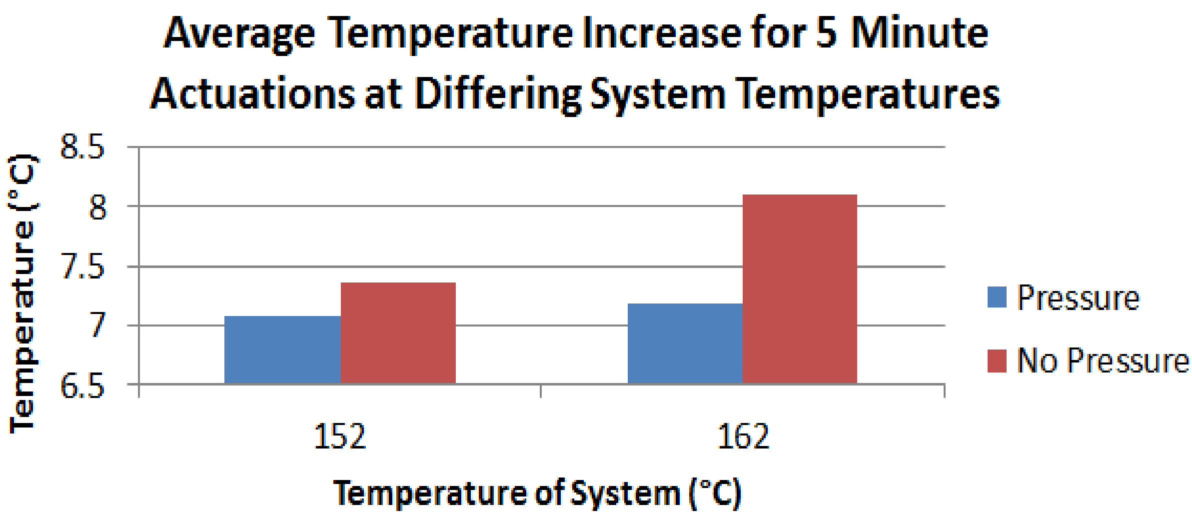

Figure 10. Graphical representation of valve temperature increase with and without pressure within the fluid line. Valve is at 152C or 162C

Take note that the average temperatures calculated increase as the time of the actuation increases. Also, note that the average temperature change with no pressure (atmospheric) is greater than that with pressure for all the actuation times tested. Furthermore, the average temperature increase for a 5 minute actuation at 162C is greater than that at 152C for both the pressure and no pressure tests.

During the testing, there were suspected contamination problems that eventually rendered the valve inoperable. The inlet and outlet lines used during the testing did not have filters to protect against contamination, but the valve failure indicates the valves are especially vulnerable to debris. This problem was also experienced with the Lee valves in the SDS during the VDU testing phase of the project. When the contamination problem was discovered, routine cleaning procedures were used to try and remove the contamination to allow the valve to function again. Several rounds of cleaning failed to restore the valve back to its operational state.

IV. Conclusions and Future Work

Currently, the data collected on the Lee valve does not warrant a replacement of the baselined Mindrum valve. Further work is required to better characterize the system and long duration testing is required to increase the TRL of the valve. The baseline design has flight heritage and analysis on the manifold system shows positive margin for stress under the expected environmental conditions. Although the cost of these valves is significantly lower than the baseline design, it requires a full redesign of the system and extensive work on thermal and mechanical design of the system. At this time we will continue to test the valve as possible (most likely with student projects), to increase the TRL and keep the valve as an option for other flight projects.

References

Captain, J.E., et al., "Design and development of volatile analysis system for analog field test of lunar exploration mission," *Advances in Space Research,* Vol. 55, 2457-2471, 2015.